Networking surface electrode ion traps for large-scale QIP

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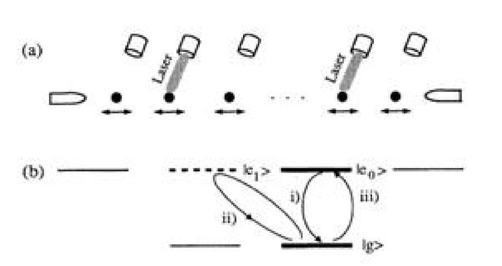
ARDA Advanced Research and Development Activity
Alexander von Humboldt Stiftung / Foundation

Towards an Ion Trap Quantum Processor

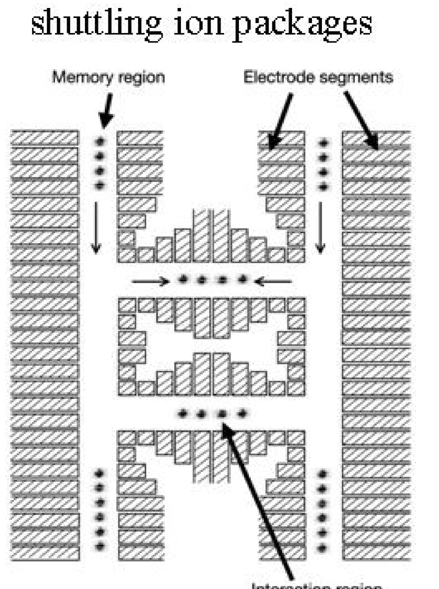
original proposal: ions in a string



Cirac and Zoller, *PRL* **74**, 4091 (1995)

improved proposal:

shuttling ion packages



Nature **417**, 709 - 711 (13 June 2002)

- Trapped ions constitute one of the most promising systems to implement scalable quantum computation
- all DiVincenzo criteria demonstrated, but

How can we scale up?

- in a single trap scaling was found to be impossible because ions in a long string require an extremely accurate control of oscillation frequencies (also extremely large radial frequencies), upper left figure
- another proposal (bottom left figure) suggested to use ion packages and to transport quantum information by shutling them through microstructures
- 2D is required to separate and join arbitrary groups of ions (e.g. necessary for entangling gates)
- sophisticated layouts implement memory units & interaction zones

How does this look like?

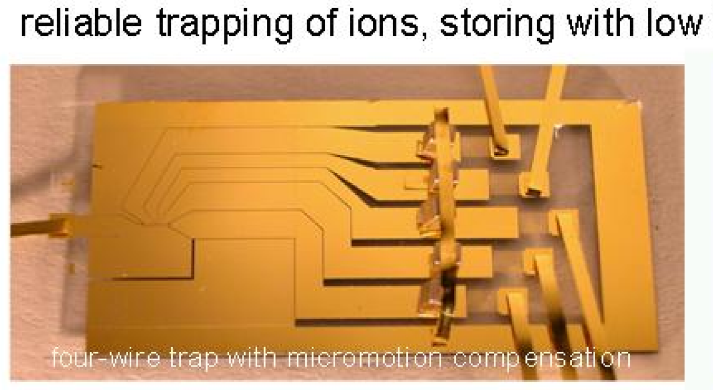
problematic issues

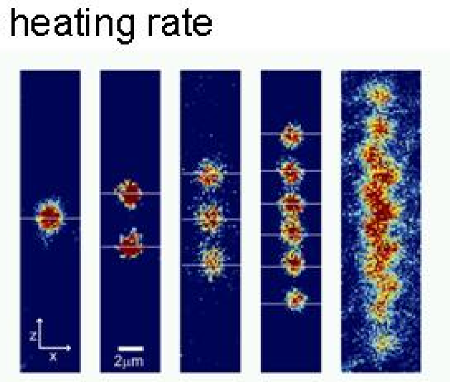
- junctions have RF barriers
- technological scalable trap layouts (simplest approach: all in a single plane)
- required resources still enormous
- ..., probably still more

Progress in surface trap layouts for QIP at NIST

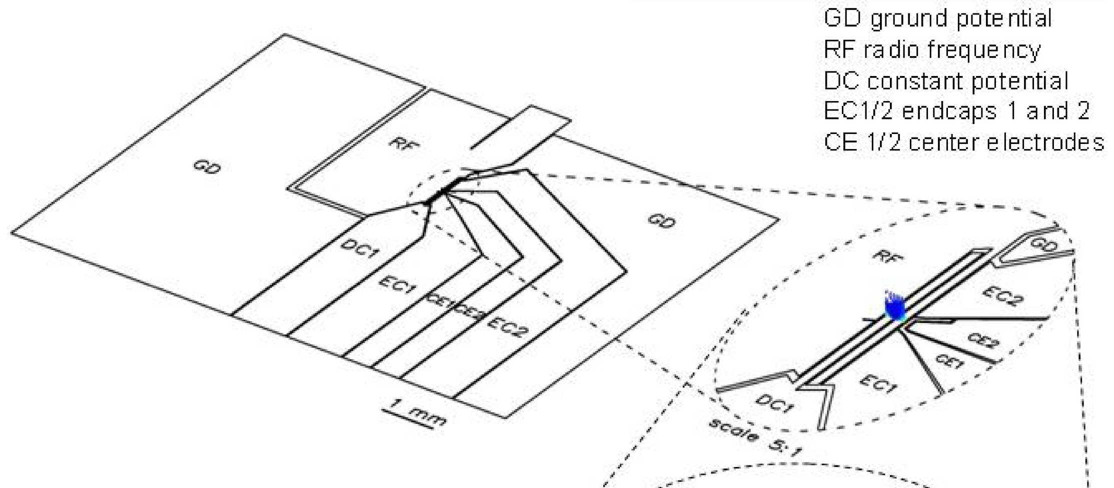
(*arXiv quant-ph/ 0601173*, 2006)

reliable trapping of ions, storing with low heating rate



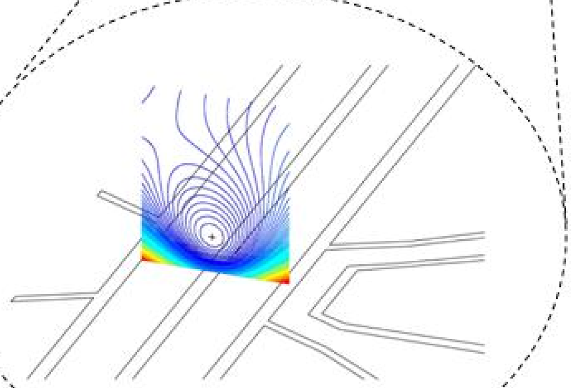


GD ground potential
RF radio frequency
DC constant potential
EC1/2 endcaps 1 and 2
CE 1/2 center electrodes



Oscillation frequencies (experimental and simulated) for three potential configurations. $f_{\parallel}$ axial frequency, $f_{\perp 1}$ and $f_{\perp 2}$ frequencies along two principal axes.

config.	$f_{\parallel}$ (MHz)	$f_{\perp 1}$ (MHz)	$f_{\perp 2}$ (MHz)	U_T (meV)	
1	2.83	15.78	17.13		(Exp.)
	2.77	15.67	17.21	177± 6	(Sim.)
2	1.84	15.87	16.93		(Exp.)
	1.75	16.23	16.87	193± 11	(Sim.)
3	2.85	5.28	8.29		(Exp.)
	2.77	5.05	8.75	6± 1	(Sim.)



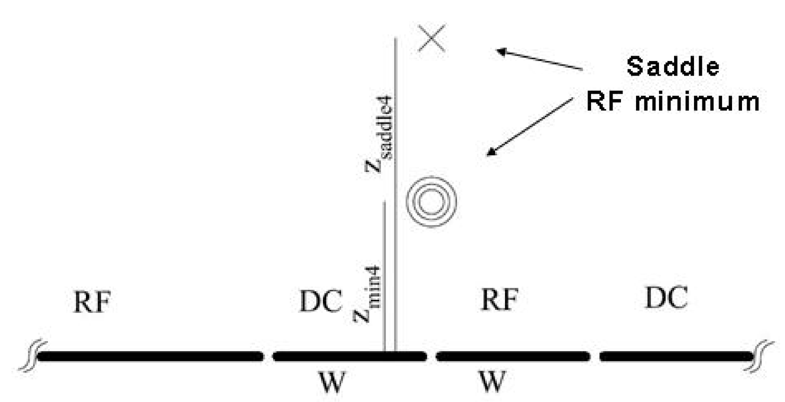
for similar approaches of other groups see C.E. Pearson *et al. arXiv quant-ph/ 0511018*, (2006)

D. Stick et al. *Nature Physics* **2**, 36 (2006)

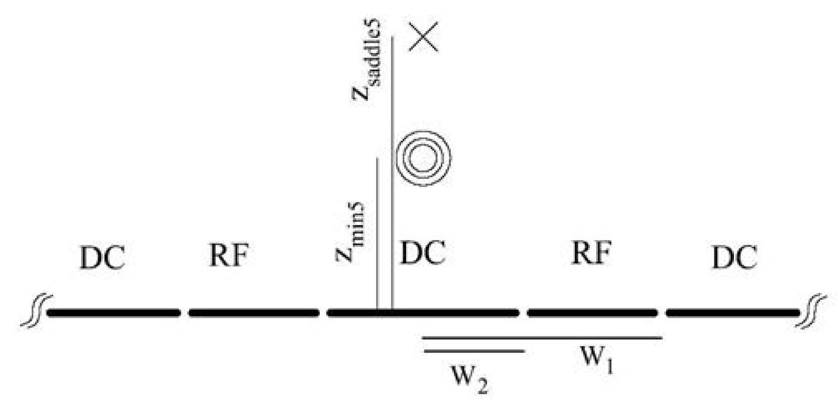
General properties of surface traps: Cross Section Model (2D)

- we solve the Laplace equation with Dirichlet boundary conditions analytically and use some idealizations from which we can derive general properties of the RF potentials of surface traps and tabulate them.
- wires extend in the 3rd dimension (out of the paper plane) and are assumed infinitely long

'four wire surface traps'/ (asymmetric four wire layouts+ground)



'five wire surface traps' / (symmetric four wire layouts+ground)



Position of RF minimum and saddle

$$z_{min4} = W$$
$$z_{saddle4} = \sqrt{2+\sqrt{5}}W \sim 2.058W,$$

$$z_{min5} = \sqrt{W_1 W_2} \equiv G(W_1, W_2)$$
$$z_{saddle5} = (W_1W_2)^{1/4}\sqrt{W_1+W_2+\sqrt{W_1W_2}},$$

Trapping depth (t.d.)

$$t.d._4(W) = \frac{Q^2V_{RF}^2}{4m\Omega^2 z_{min4}^2}\cdot\frac{2}{\pi^2(11+5\sqrt{5})}$$
$\equiv t.d._{hyp}$ ~ 0.00914

$$t.d._5(W_1,W_2) = \frac{Q^2V_{RF}^2}{4\pi^2 m\Omega^2}\times\frac{A(W_1,W_2)-G(W_1,W_2)}{A(W_1,W_2)^2(A(W_1,W_2)+G(W_1,W_2))}$$

$A(), G()$ arithmetic, geometric mean, respectively

maximal for $A(W_1,W_2)/G(W_1,W_2) = \frac{1+\sqrt{5}}{2} = g$ (1) GOLDEN RATIO

using the last relation yields $\boxed{t.d._{max5} \equiv t.d._4}$

optimum geometry from (1) $\hat{W}_{1/2} = W_{1/2}/z_{min5} = g \pm \sqrt{g}$

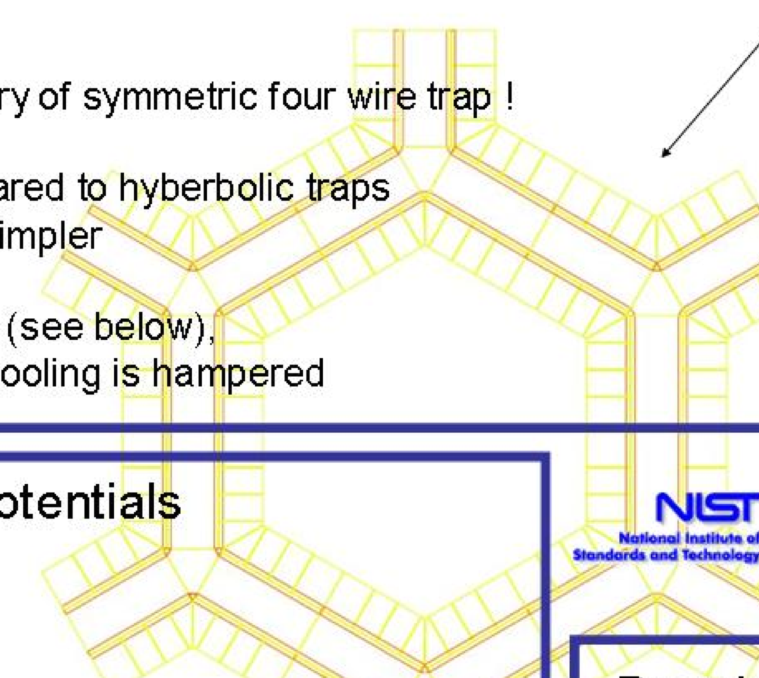
Trapping Frequencies

$$\omega_z \equiv \omega_x = \frac{QV_{RF}}{\sqrt{2}m\Omega z_{min4}^2}\cdot\frac{1}{\pi}$$
$\equiv \omega_{hyp}$ ~ 0.318 reduction factor

$$\omega_z \equiv \omega_x = \frac{QV_{RF}}{\sqrt{2}m\Omega z_{min5}^2}\cdot\frac{2}{\pi}\sqrt{\frac{1+\sqrt{5}}{7+3\sqrt{5}}}$$
$\equiv \omega_{hyp}$ ~ 0.309 reduction factor

Conclusions:

* trapping depths of symmetric and asymmetric layouts are *identical* for ideal geometry of symmetric four wire trap !
* their t.d.'s are lowered to ~1% of the trap depths of a hyberbolic trap
* frequencies are only slightly higher for the asymmetric layout, and about 0.31 compared to hyperbolic traps
* but: surface traps can be easily manufactured on a much smaller length scale and simpler
* pro&con of asymmetric and symmetric layouts:
  symmetric arrangement is simpler to realize technically and preferable in junctions (see below),
  principal axes are parallel and perpendicular for symmetric layouts, thus Doppler cooling is hampered

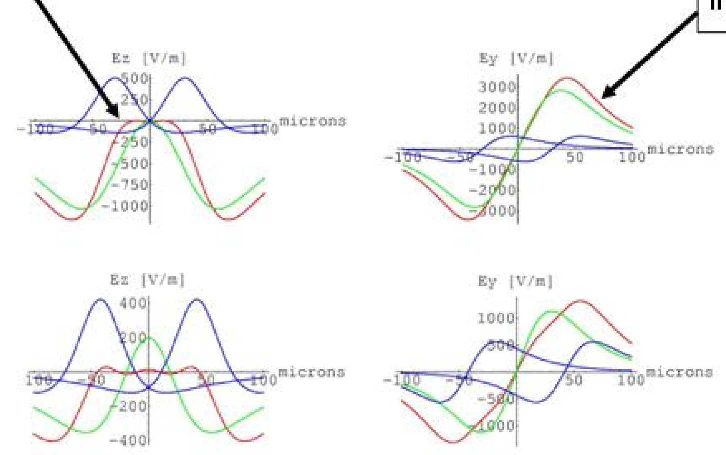


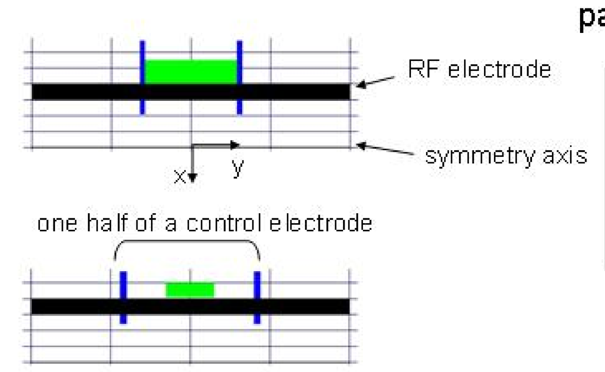
Geometrical compensation of micromotion and nearly parabolic potentials

Control electrodes can be designed to have only an E field component in a single planar dimension, e.g. along the trap axis, over a distance longer than the average electrode length !

Ez field (vertical component) is nearly zero over electrode length, thus no induced micromotion

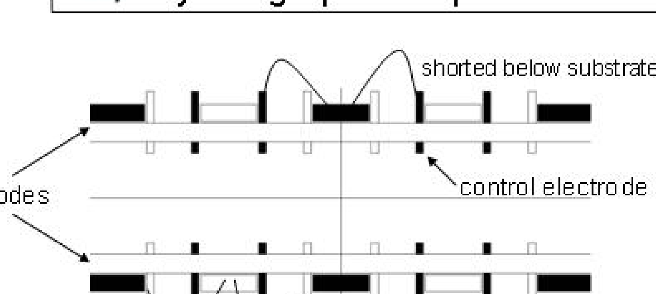
linear over almost an electrode width





A linear Ey field helps to **decrease higher order contributions** to the approximate parabolic trapping potential at various sites.

Interlacing DC electrodes increases the preferred properties over a longer distance, e.g. about 1 ½ average electrode widths and helps to save resources
⇨ **only a single potential per electrode!**



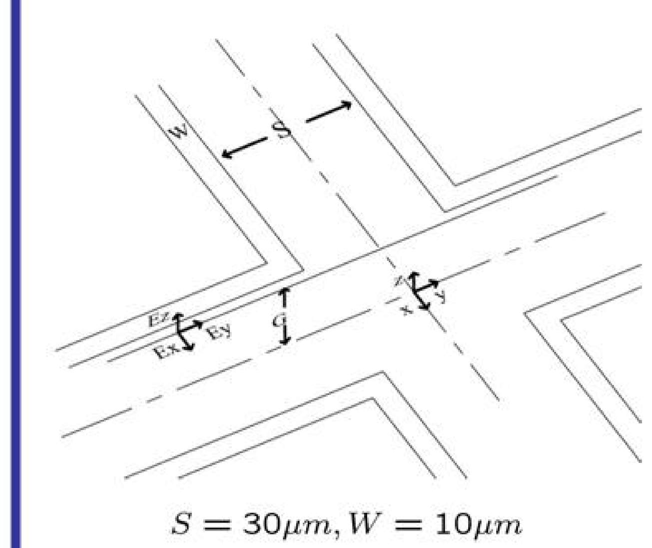
the colors blue and green refer to the electrode parts on the right with the same color. Red represents the whole electrode, i.e. the sum of both parts.

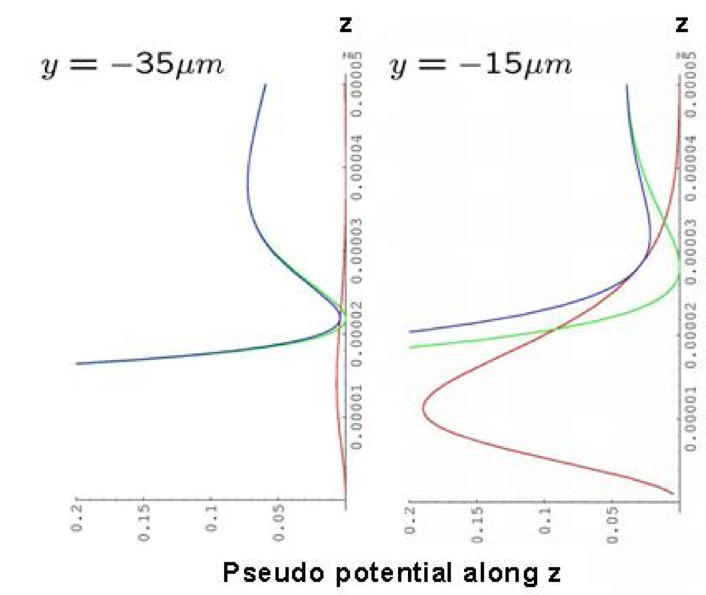
Crossing points at junctions (nodal points)

networking requires implementation of junctions
Basic principle: transform from a 2D dynamic 1D static trapping (outside of a junction) to a 1D dynamic 2D static potential (center of junction)

Pseudo potential$(x=0) \propto (E_y^2(y,z)+E_z^2(y,z))$
$E_y^2 = (E_{y1}+E_{y2})^2$
$E_z^2 = (E_{z1}+E_{z2})^2$

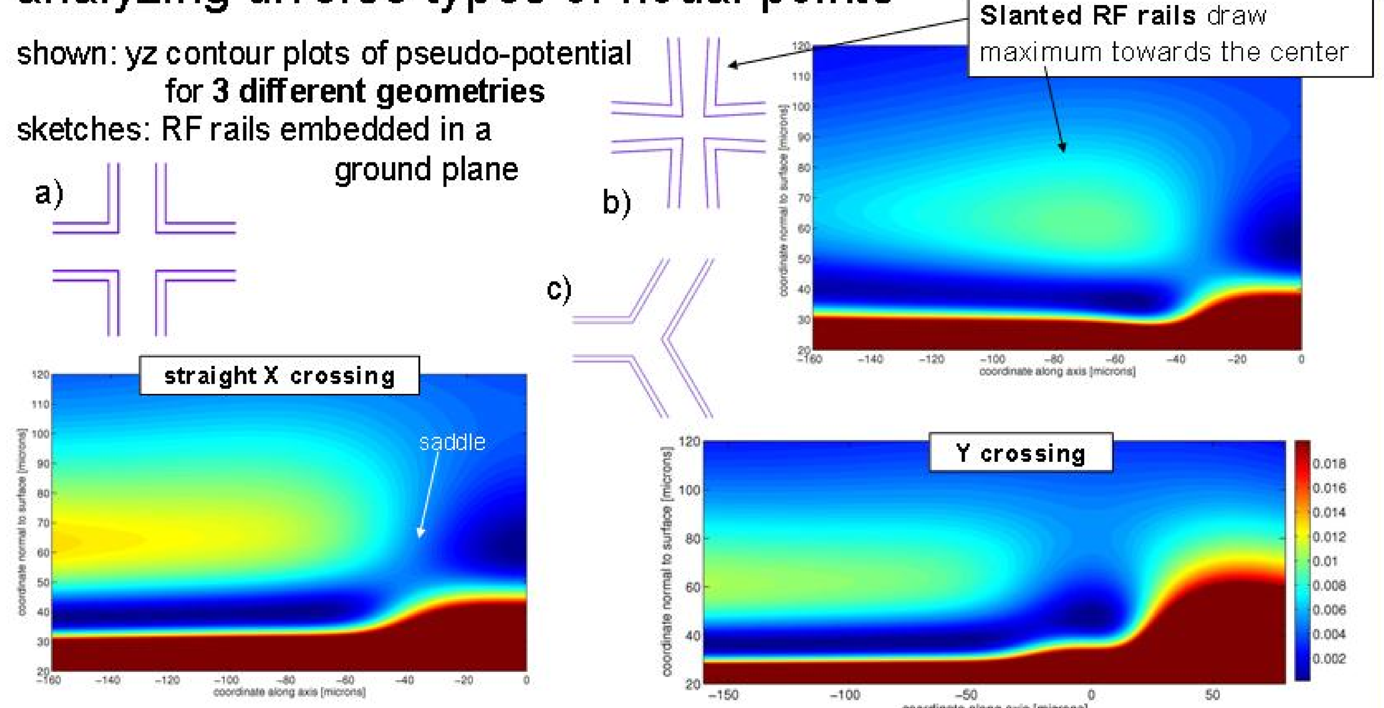
problems are RF bumps resulting from edge singularities in Ey !
Anit-binding can result





analyzing diverse types of nodal points

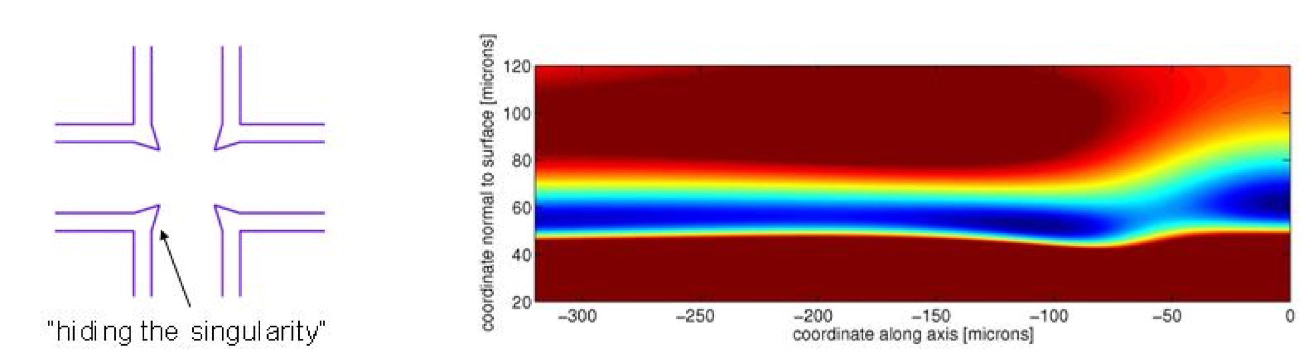
shown: yz contour plots of pseudo-potential for **3 different geometries**
sketches: RF rails embedded in a ground plane



Y junctions are preferable and exhibit a smoother behaviour at junctions !

2) another possibility is to use compensation structures

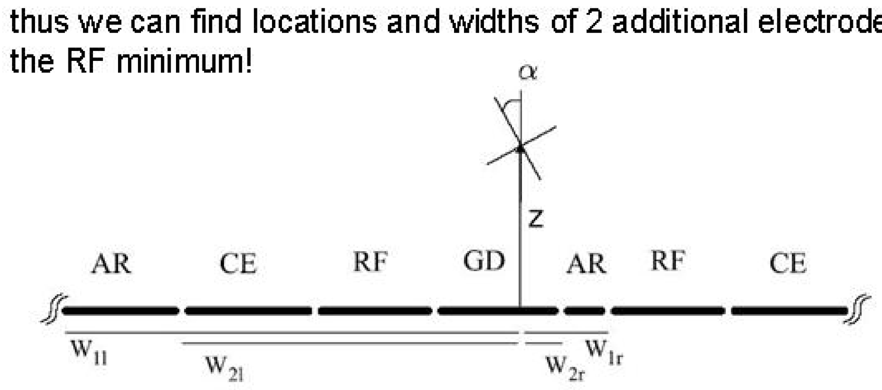
modified electrode shapes near the cross help to smooth characteristics near nodal points (reduce effect of singularities)



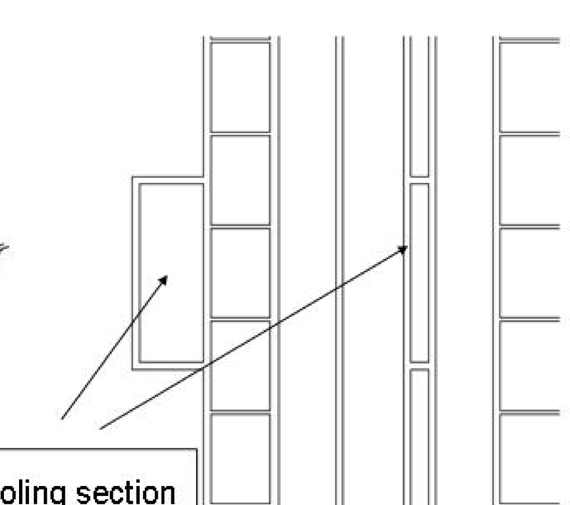
Doppler cooling in 'symmetric four wire traps' (5 wire traps)

From analytical theory follows $4z(W_1+W_2)\tan\alpha - (W_1+W_2)^2 + (W_1-W_2)^2/4 + 4z^2 = 0$

thus we can find locations and widths of 2 additional electrodes (AR) to force a rotated saddle at the RF minimum!



AR axes rotation electrode
CE control electrode
RF radiofrequency electrode
GD ground



Doppler cooling section